

LONG TERM CHANGE AND DOCUMENTATION BY PHOTOGRAMMETRY FOR THE PRESERVATION OF EARTHEN ARCHAEOLOGICAL SITE

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ABSTRACT

Scientific documentation with digital photogrammetry was applied to an earthen archaeological site in the project 'Preservation of the Buddhist Monastery of Ajina Tapa, Tajikistan'. The decayed earthen walls of the monument have been recorded and three dimensional mapping of the total site has been done. The process of structural damage of earthen materials is related to the change in the shape of the walls of the monument as recorded by close-range photogrammetry over a period of nine month. This analysis provided useful information for the project, conservation and preservation of the site. The damaged walls were covered with new mud brick and mud plaster. The walls are designed not to be vertical and the bottom is thicker than the top. This is both to prevent the failure or collapse of the walls and to reduce the decay caused by salt weathering. In addition, photogrammetric analysis also applied to the repaired walls, after the conservation work had been carried out. The results monitor that the damaged walls fully covered by new earthen materials. Documentation with photogrammetry is very effective method for conservation and maintenance of archaeological site. This method might be potential for modern structure of civil engineering.

KEYWORDS: deterioration, earthen materials, image analysis, salt weathering, close-range photogrammetry

1. INTRODUCTION

This article is a part of Doctoral Thesis "Long term change, fault and fabric structure of geosphere materials by image analysis". The thesis includes some topics, earthen archeological and sandstone materials analyzed by image analysis of photogrammetry and stereology. In this article, earthen archaeological site documented by photogrammetry is picked up. Because this topic has especially strong impact on society and field of civil engineering.

Conservation and preservation works for the heritage sites have been recently conducted on many ancient areas in the world. Geo-engineers and geo-technicians have potential to contribute to such works with the knowledge of rock and soil mechanics, rock weathering, and the related technique.

Scientific documentation is the most basic method for conservation and maintenance of archaeological site. Monitoring of earthen archaeological sites is very essential for conservation and preservation of the site. The application of monitoring and maintenance to the archaeological site might be contributed to the preservation of modern infrastructure in civil and architectural engineering.

The project 'Preservation of the Buddhist Monastery of Ajina Tapa, Tajikistan (Heritage of the Ancient Silk Roads)' is one of the operational schemes launched by the UNESCO/Japan Trust Fund in central Asia, from 2005 to 2008. The main objectives of the project are: the scientific documentation of the site; the establishment of a master plan for the site; the application of appropriate conservation and maintenance schemes; the development of promotional activities at both national and international level; and the training of people in the maintenance, conservation, and monitoring of earthen archaeological sites.

As one of the scientific aims of the project, documentation with digital photogrammetry was applied to the decayed earthen walls of the monument. This photogrammetric technique has been successfully employed in the field of engineering and science in relation to aerial photographs (Mikhail et al., 2001). Recently, close-range photogrammetry (Atkinson, 2001) has been applied not only to cultural heritage sites for documentation purposes (Koutsoudis et al., 2007; Yastikli, 2007; Yilmaz et al., 2007; Fujii et al., 2007a), but also to the geological and geotechnical fields as a measurement tool (Fujii et al., 2007a; Fujii et al., 2007b).

In this study, the process of structural damage of earthen materials is related to the change in the shape of the walls of the monument as recorded by close-range photogrammetry over a period of nine months (Fujii et al., 2009). This analysis is intended to provide useful information for the conservation and preservation of the site. In addition, close-range photogrammetry was also applied to the repaired same monument as the monitoring method.

2. STUDY AREA

2.1 The site of Ajina Tapa

Ajina Tapa is located near Kurgan Tyube, which is about 100 km south from Dushanbe, the capital city of Tajikistan. And this area is west of the Pamir Mountains (Fig. 1), at an average elevation of 500 m above sea level. The climate of this area is considered as continental steppe. Rainfall is concentrated in the winter season and is rare in the summer when solar radiation is intense. The average annual precipitation was about 260 mm/year during the period from 1961 to 1990 as according to the world weather information service in the town of Kurgan-Tube (located about 15 km west from Ajina Tapa).

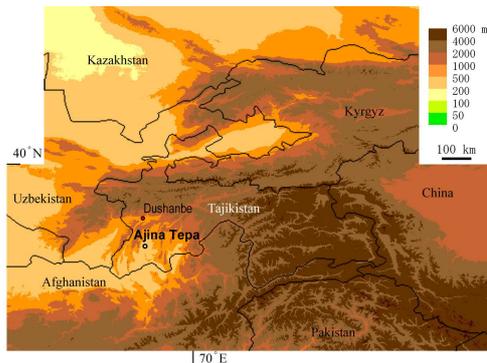


Fig. 1 Index map of Ajina Tapa (basal map is from Global Map, <http://www.iscgm.org/>).

The geology around the site is composed of Cretaceous sedimentary rocks which are covered with Tertiary sediments (Commission for the Geological Map of the World, 1981). Loess is widely distributed in this area, and this is originated from the weathering of rocks and sediments. These aeolian deposits are predominant in the central Asian steppes. They have particle sizes towards the fine end of the soil index and have no gravel (Fodde, et al, 2007). In addition, they can have carbonates and salts at a high level when compared with other types of soils (Fodde, 2008, Fodde et al., 2014).

The Ajina Tapa site is currently surrounded by a broad swath of cotton fields. There are irrigation canals which reach a depth of about a few meter below the level of the site and the cotton fields.

Two of them flow along the south-east and -west sides of the archaeological site.

2.2 The monastery of Ajina Tapa

The monastery of Ajina Tapa has been dated to between the 7th and 8th centuries AD. Systematic excavations were done under the supervision of experts from the Moscow Institute of Oriental Studies, which is part of the Russian Academy of Science from 1961 to 1975. Much of the information produced was stored in the archives and a report was published in Russian and English (Litvinskij and Zejmal, 2004). According to that report, the monastery of Ajina Tapa was made of two parts: the monastery area (featuring an open courtyard measuring 19 m×19 m); and the temple area (which has a massive terraced stupa, a Buddhist shrine, in the courtyard; Fig. 2). Both mud brick and pakhsa (rammed earth) were used for the construction of the monastery walls. Those materials are made of loess and other local earthen materials. Pakhsa was generally found at the lower level, about 15–20 cm above the floor (Litvinskij and Zejmal, 2004). During the excavation, a 13 meter-long sleeping Buddha was discovered in one of the corridors. The Buddha, made of soil and mud plaster, was cut into pieces and transported to the National Museum of Antiquities of Tajikistan, in Dushanbe. It was conserved and displayed in the museum. It is considered to be the largest Buddha in central Asia after the destruction of the Bamiyan statues in Afghanistan in 2001.

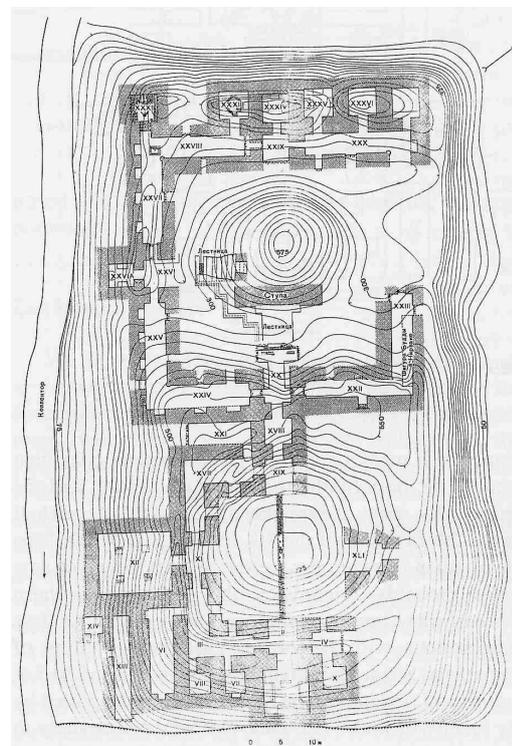


Fig. 2 Topographic map and plan of the building, Ajina Tapa excavated by the Moscow Institute of Oriental Studies (Litvinskij and Zejmal, 2004)

After the excavation, no protection or preservation work was carried out on the buildings of the monastery. The site is badly decayed and reconstruction of the original shape of the walls will be difficult.

3. DOCUMENTATION METHOD

3.1 Digital photogrammetry

Photogrammetry is the process of deriving metric information about an object through measurement on photographs of the object (Mikhail et al., 2001). Obviously, two-dimensional co-ordinate can be gained from a single photo (two-dimensional plane). If we have two photos of the same object from different directions, we can get three-dimensional co-ordinates of the object (Fig. 3).

Historically, photogrammetry has been used to construct topographic maps from stereo-photographic pairs of aerial photographs. The technique can be applied to close-range observations with a hand-held camera and lens. The close-range photogrammetry has been applied to many kind of objects (Atkinson, 2001).

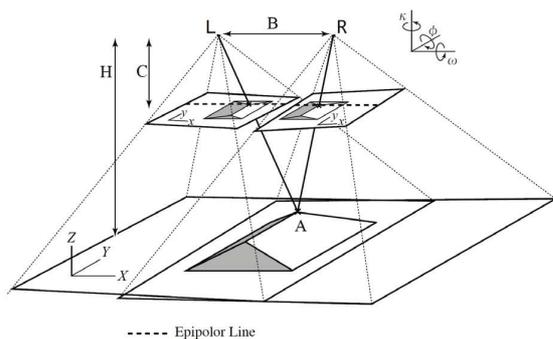


Fig. 3 Overlapping pairs of stereo-photographs and a target object

L: left camera. R: right camera. x, y : 2-D coordinate on the photographs. X, Y, Z : 3-D coordinate for the camera positions and the target objects. ω, ϕ, κ : orientation parameters for the left and right cameras H : the distance from the cameras to the object. B : the distance between two cameras. C : focal length of the camera (lens). A : an arbitrary point on the object. The plane defined by the three points, L, R , and A is an epipolar plane. The two lines where this plane intersects the two photographs are refer to as epipolar lines (break lines).

3.2 Digital terrain models of the damaged walls

A three-dimensional (3-D) morphology can be produced from a pair of overlapping stereo-images. The information of camera positions and orientations ($X, Y, Z, \omega, \phi, \kappa$ for left and right cameras) are needed to get the three-dimensional co-ordinates of the target object (Fig. 3). However, it is difficult to get the accurate positions and directions at the same time when taking a pair of photographs. Control points, of which the 3-D co-

ordinates are measured in advance, are included in the photograph (Fig. 4). Total Station was applied to measure the control points. The Total Station (TS) is an optical measurement for surveying that is formed by an electronic theodolite, an electronic distance measuring tool and an external computer. The camera positions and directions can be inversely calculated from the control points by means of least-square adjustments (LSA) with 3-D digital photogrammetric software. At least five control points, which might be spread over the object wall, can be needed for the calculation of the camera positions and directions. After the LSA in the stereo-photogrammetric program, the residuals can be calculated for each pair of stereo-photographs.



Fig. 4 A pair of stereo-photographs of a damaged wall (Wall A). Crossed circles on the left photograph show control points

After the calculation of camera positions, the software can give matching of the same positions on epipolar lines over a pair of digital images by means of the difference of color and contrast, and generates 3-D coordinates of the points. The epipolar lines are two lines where epipolar plane intersects a pair of overlapping photographs. The epipolar plane is known as the plane defined by the three points L, R , and A (Fig. 3). The 3-D data of about 3,000 points were generated on the photographs. Those points are connected with lines and the surface morphology of the wall is constructed as a Triangle Irregular Network (Fig. 5). The great advantage of digital photogrammetry is to connect the photo images to a Digital Terrain Model (DTM). The result is a texture mapping model, which can be viewed from multiple directions.



Fig. 5 Triangle Irregular Network (TIN) on a stereo-pair of photographs, Wall A

3.3 Construction of topographic map

Close-range photogrammetry has been applied not only to the walls but also the topography of the whole site. Generally, aerial photographs are suitable for making a topographic map of a wide area. However, this study did not have the opportunity to take high resolution aerial photographs of the site for stereo-photogrammetric purposes.

Therefore 14 pairs of stereo-photographs were taken in the site of Ajina Tapa. These photographs almost cover the total area of Ajina Tapa. However, some areas in the photographs were hidden by high monument walls. For example, in a pair of overlapping photographs, which was taken from the top of the Stupa, some areas are hidden by the monument walls (arrows in Fig. 6). 3-D information cannot be gained in such areas.



Fig. 6 A pair of stereo-photographs taken from the top of Stupa. Arrows show hidden areas by walls.

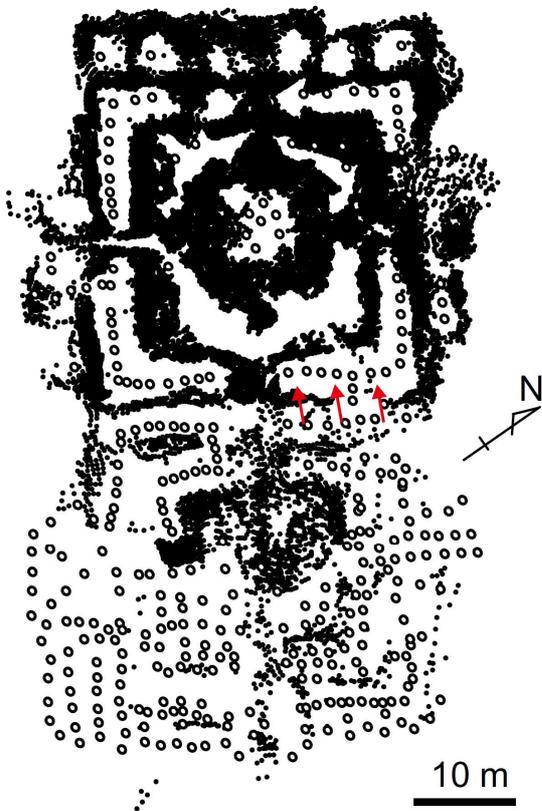


Fig. 7 3-D points gained from photogrammetry (black circles) and TS (white circles).

Black circles in Fig. 7 show 3-D points which were gained from 14 pairs of stereo-photographs. Some blank areas show hidden areas in the photographs such as Fig. 6 (arrows). Direct measurements were applied for the hidden areas with TS. Newly gained 3-D points (white circles in Figure 7) were added into the photogrammetric data.

The points gained from both photogrammetry and direct measurement has been used to make topographic map of the site. Fig. 8 shows the total map of the site. It is a Digital Elevation Model (DEM) with elevation encoded by intensity values, with brighter values being higher, and overlaid by 1 meter contour lines.

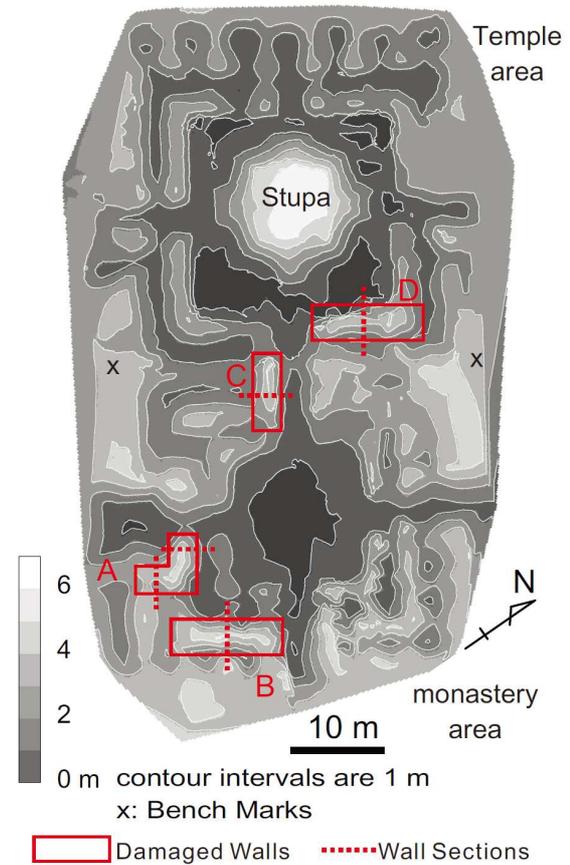


Fig. 8 Total map of Ajina Tapa. The site is composed of two parts, northwestern temple (stupa) area and southeastern monastery area.

4. RESULTS

4.1 Morphology of Damaged Wall

Four damaged walls (Fig. 9) were mapped in 3-D with digital photogrammetry. Apart from Wall A, two pairs of photographs were taken of each wall to make DTMs of both the sides. Wall A (Fig. 8) is a reversed L-shape in ground plan, so pairs of photographs of the northeast and southeast sides were taken from the northeast and southeast respectively. Another pair of photographs of the L-

shaped wall was taken from the southwest (Fig. 4). The control points for each pair of stereo-photographs were given 3-D co-ordinate defined by the benchmarks (Fig. 8). In this way the original position of each DTM was established and complete cross-sections of each wall were obtained (Fig. 9). The massive wall had been constructed with pakhsa blocks or mud bricks on pakhsa base, and the original shape of the section may have been rectangular. The original thickness of the wall was 2.4 m, which was recorded by Litvinskij and Zejmal (2004). The original height of the wall is not clear for Wall A, but the walls of the monastery area had an average height of 2.5 m with a maximum height of 5 m (Litvinskij and Zejmal, 2004). The maximum width of the remaining wall is about 2 m (Fig. 9). The current shape of the wall is very different from the original rectangle because of erosion. First, the upper part of the wall was strongly eroded and has become rounded. Both sides (north and south) are eroded deeply, a little more prominently on the north side than on the south. Second, the basal part of the wall was undermined to make shallow coves and was eroded asymmetrically. Its south side was more deeply eroded than north side. Some measured sections of damaged walls are shown in Fig. 9a–d. Fig. 9b shows an east–west section of Wall B, which is situated at the southern monastery area and oriented in a north–south direction (Fig. 8). The upper part of the wall is eroded and the top is rounded. Both east and west sides are equally eroded. The maximum width is now about 1.5 m, which is considerably thinner than the original thickness of 2.4 m. The basal part is more deeply eroded than the middle part of the wall. Other damaged walls show more or less similar features, irrespective of their positions and orientations. Common characteristics of the erosion are as follows:

1. The walls are significantly eroded compared with the original outlines.
2. The top of the walls are eroded and rounded.
3. The basal part is more undermined and thinner than middle part of the walls.

4.2 Monitoring of Wall A

Rapid erosion can be seen at the south-eastern end of Wall A, with the basal part being severely eroded when it was measured in August, 2006 (broken lines in Fig. 10). The height of the wall was then about 4 m, but the basal part about 0.5 m to 0.8 m above the ground surface was deeply undermined. The maximum depth of the erosion was about 0.6 m and looks like a notch. About nine months later, the top and middle parts of the wall had collapsed and the surface of the wall had become simple plane by May 2007 (solid lines in Fig. 10). The volume of the collapsed part is about 1.6 m³, which is calculated from a series of sections made by photogrammetric measurements. The sections measured in 2006 and 2007 are made from DTMs which were calculated from the same 10 control points. Therefore, the sections are almost identical except for the collapsed or eroded parts (Fig.10). These data obtained by digital photogrammetry provide the quantitative basis for evaluating the advance of the erosion of the wall. In this way, the progress of the deterioration of the walls of Ajina Tapa was recorded.

5. DISCUSSION

5.1 Erosion by Rain and Wind

Prior to the original excavations, the site was totally covered with sediments and appeared as a mound (Litvinskij and Zejmal, 2004). After the excavations, there was no appropriate preservation or protection work carried out on the buildings. Therefore, the building walls have been exposed since 1975. The erosion rates are relatively slow for mud brick and medium for pakhsa and the wetting and drying test shows very little failure for both materials (Fodde et al., 2008a). Therefore, it appears that rain or wind have been main erosive agents for the tops of the walls for about 30 years. Winter is the rainy season in the area of Ajina Tapa, so the walls are more strongly eroded by rain water in such season. The building wall was badly eroded, resulting in the rounding of the top of the building walls (Fig. 11).

5.2 Decay Mechanism at the Basal Part

In Central Asia region, salt crystallization or salt attack is an important erosion agent that causes decay of the basal part of walls in earthen archeological sites. The average soluble salt content of earthen material was calculated in three central Asian historic sites: 4.7% in Ajina Tapa, Tajikstan (Fodde, 2008), 3.8% in Krasnaya Rechka,

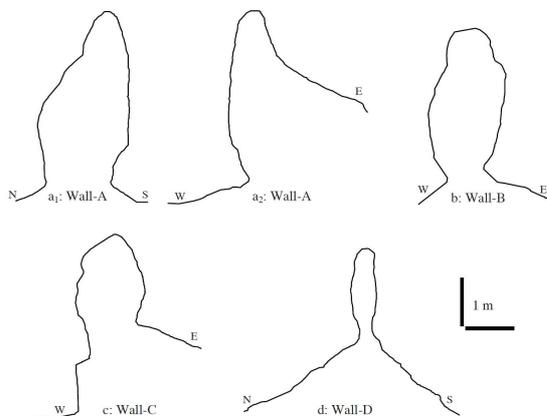


Fig. 9 Sections of the damaged walls. See Fig. 8 for locations of the walls.

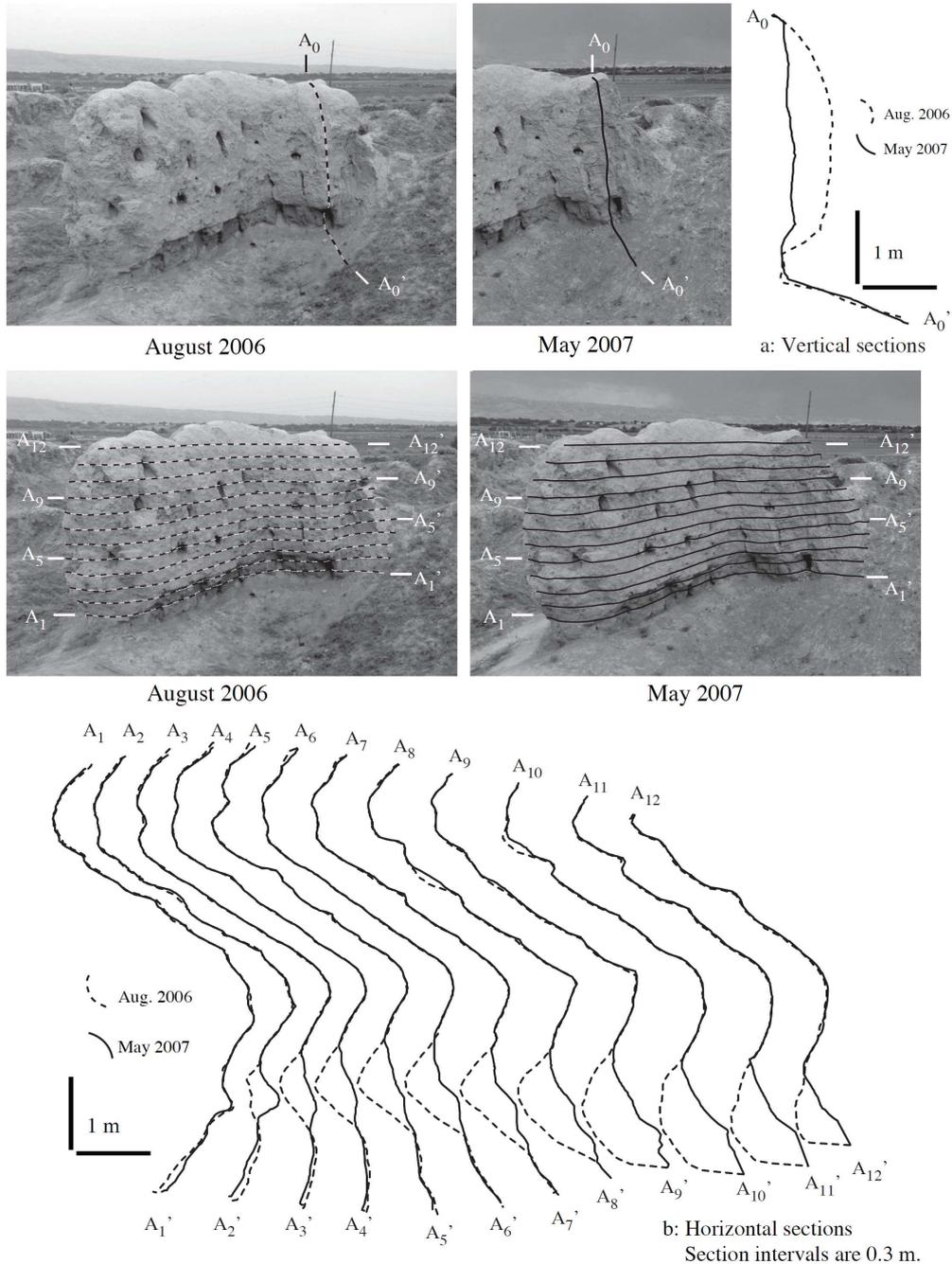


Fig. 10 Change of Wall A (L-shaped segment). Upper row: views from southwest, left in 2006, right in 2007. a: Vertical profiles. Middle row: photos showing reference horizontal sections, left in 2006, right in 2007. Lower row: ground plans of the reference horizontal sections. Southern rim collapsed between August 2006 and May 2007 (Fujii et al., 2009).

Kyrgyzstan (Fodde, 2007c) and, 5.6% in Otrar Tobe, Kazakhstan (Fodde, 2007b). At Ajina Tepa, salt is actually crystallized on the excavated surfaces of the walls. It was analyzed by X-ray diffraction, and halite, calcite and gypsum found to be the major salt minerals crystallized on the walls. Mud brick and pakhsa both contain soluble salt and these salts may be transported by groundwater. Vertical profiles of evaporation rates were measured on the surface of the walls (Watanabe et al., 2008), and demonstrated that the rate is greatest

at ground level and gradually decreases with the height. This indicates that the moisture is essentially supplied from groundwater. At a height of 1 m above the ground, the evaporation rate is small compared with ground level. The erosion of the basal part of each wall is less than 1 m in height. It is clear that soluble salts were transported to the surface by capillary groundwater and crystallized on the basal part of the walls as the groundwater evaporated. The south-east and -west side of the site is along the irrigation canals, so groundwater

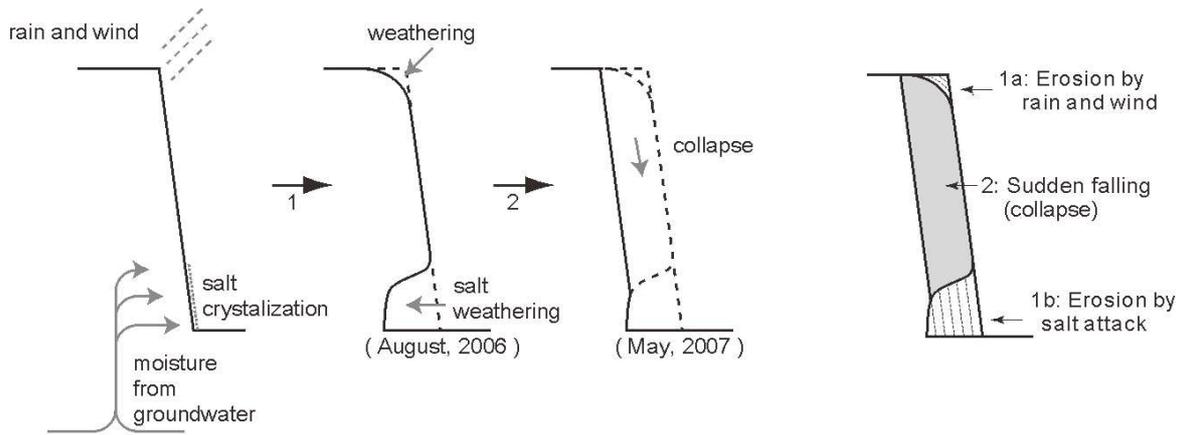


Fig. 11 Schematic erosional process of the wall. 1: Soluble salt is transported with capillary groundwater, and crystallized on the surface of the wall. Salt crystallization attacks and erodes the basal part of the wall. The top part of the wall is also eroded by rain and wind. 2: The upper wall, which lost support due to the thinning of the basal part, collapses suddenly. The wall surface becomes planar, and the erosion will continue to decay the wall. (Modified from Fujii et al., 2009)

can readily seep on to the floor and evaporate in the summer sun. The salts cause damage to the wall (Goudie and Viles, 1997) and the combination of wind and windblown silt adds strength to the forces of erosion. With annual repetitions of the process, the basal part of the walls became thinner than the middle part (Fig. 11-1).

5.3 Wall collapse

Due to the thinning of the basal part of the walls by salt attack, the upper sections lost support from the base. Eventually, the undermined part of the wall collapsed under its own weight (Fig. 11-2). The collapse is caused by structural weakness, particularly in the rainy winter season, when the earthen materials contain more moisture and have less strength. In addition, earthquake and other external forces may have precipitated a sudden failure in the wall. The wall becomes thinner and the surface is planar after a collapse event, but the decay continues under the effects of soluble salt attack, rain, and wind (Fig. 11).

6. CONSERVATION AND CONCLUSION

Some conservation works have been carried out on this project (Fodde et al., 2007) to the extent that some unstable walls have been supported by buttresses made of new mud brick and plaster (Fig. 12). The walls are designed not to be vertical and the bottom is thicker than the top. This is both to prevent the failure or collapse of the walls and to reduce the decay caused by salt weathering. Wall A had been also repaired with new mud brick and plaster. In addition post-repaired structure has been also documented by photogrammetry. Fig. 13 shows sections both before and after the conservation work. Historical damaged wall had been fully covered by new mud brick and new plaster. It can be shown in Fig. 13 on the results of photogrammetric monitoring.



Fig. 12 An example of conservation work. Wall B is supported by buttresses made of new mud bricks. New mud bricks would be covered by new mud plaster as Fig. 13.

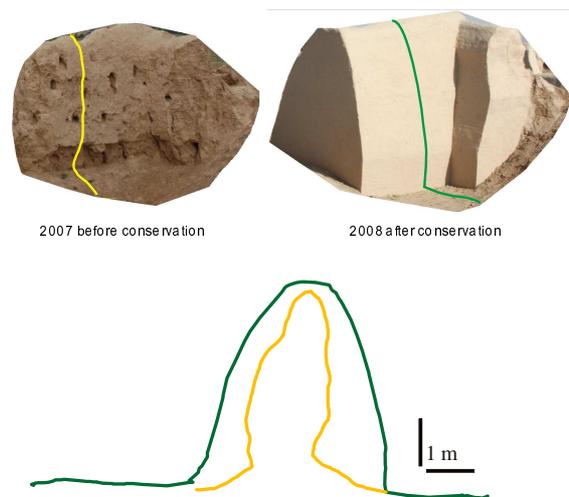


Fig. 13 Texture mappings and sections of Wall A, pre- and post-conservation work. Upper left shows a pre-conservation texture mapping, upper right shows a post-conservation one. Lower shows their sections.

Scientific documentation constitutes one of the central elements of the UNESCO/Japan Trust Fund preservation project at the archeological site of Ajina Tapa. Three dimensional mapping of the Buddhist monastery was done as part of the project. This included using digital stereo-photogrammetry to map four unstable walls that had already been damaged to varying degrees by erosion and collapse. Rain and wind have eroded the top part of the walls as rounded. In addition, salt attack caused the erosion of the basal part of the walls, thinning the walls and causing the upper and middle parts to collapse due to the loss of structural support from the underlying basal part. Establishing the rate of erosion in the site would be interesting, but this requires further investigation and monitoring. It has been difficult to identify precisely when, during the last 30 years, collapse occurred for each wall. For example, Wall D is now much thinner than its original 2.4 meter thickness (Litvinskij and Zejmal, 2004). Both sides of the wall show evidence of collapse, as there are residual sediments on both sides of the wall (Fig. 9d) and the collapse was prior to that of Wall A. This indicates that the speed of erosion is variable in different locations within the site. It is recommended that erosion be specifically studied to find an effective method of preservation for the site.

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8. REFERENCES

- Atkinson, K.B., (2003) “*Close Range Photogrammetry and Machine Vision*,” Whittles Pub, London.
- Commission for the Geological Map of the World, (1981) “*Geological World Atlas Sheet 11*,” UNESCO, Paris.
- Fodde, E., (2008) “Structural faults in earthen archaeological sites in Central Asia: analysis and repair methods,” In: d'Ayala, D., Fodde, E. (Eds.), *Sixth International Conference on Structural Analysis of Historic Construction*, Taylor & Francis, London, pp. 1415–1422.
- Fodde, E., Watanabe, K., Fujii, Y., (2007) “Preservation of earthen sites in remote areas: the Buddhist monastery of Ajina Tapa, Tajikistan,” *Conservation and Management of Archaeological Sites* V. 9, (No. 4), pp. 194-218.
- Fodde, E., Watanabe, K., Fujii, Y., (2014) “Measuring evaporation distribution of mud brick and rammed earth,” *Structural Survey*, V. 32 (in press).
- Fujii, Y., Takemura, T., Takahashi, M., Lin, W., (2007a) “Surface features of uniaxial tensile fractures and their relation to rock anisotropy in Inada granite,” *International Journal of Rock Mechanics and Mining Science* V. 44, pp. 98–107.
- Fujii, Y., Takahashi, M., Hori, S., (2007b) “Three-dimensional topography of fracture surfaces obtained by a digital photogrammetric technique,” *International Journal of the JCRM*, V. 3, pp. 29–34.
- Fujii, Y., Fodde, E., Watanabe, K. and Murakami K. (2009) “Digital Photogrammetry for the Documentation of Structural Damage in Earthen Archaeological Sites: the case of Ajina Tapa, Tajikistan,” *Engineering Geology*, V. 105, pp. 124-133. doi: 10.1016/j.enggeo.2008.11.012.
- Koutsoudis, A., Arnaoutoglou, F., Chamzas, C., (2007) “On 3D reconstruction of the old city of Xanthi. A minimum budget approach to virtual touring based on photogrammetry,” *Journal of Cultural Heritage* V. 8, pp. 26–31.
- Litvinskij, B., Zejmal, T.I., 2004. The Buddhist Monastery of Ajina Tapa, Tajikistan. Isiao, Rome. 190 pp.
- Mikhail, E. M., Bethel, J. S., McGlone J. C., (2001) “*Introduction to modern photogrammetry*,” John Wiley & Sons, Inc., New York.
- Yastikli, N., (2007) “Documentation of cultural heritage using digital photogrammetry and laser scanning,” *Journal of Cultural Heritage* V. 8, pp. 423–427.
- Yilmaz, H.M., Yakar, M., Gulec, S.A., Dulgerler, O.N., (2007) “Importance of digital close range photogrammetry in documentation of cultural heritage,” *Journal of Cultural Heritage* V. 8, pp. 428–433.